The UV Background and the Lyα Clouds at High Redshift[4]

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Abstract. The estimate of the ionizing UV background through the proximity effect analysis is discussed. Taking into account the correct bending of the column density distribution which appears in high resolution high s/n data, a value of the UV background $\sim 5 \times 10^{-22}$ cgs is obtained in the redshift interval $z = 1.7 - 4.1$ without indication of any appreciable redshift evolution. Inferences on the spectral shape of the UV background between the HI and HeII edges are provided by the study of metal line ratios like SiIV/CIV in optically thin systems. The presence of a jump near the HeII edge seems favoured at very high redshifts $z > 3$. An increasing HeII jump with increasing redshift can be responsible for the decreasing in the minimum temperatures of the Lyα clouds with increasing z. New studies of the cosmic evolution of star-forming galaxies allow the estimate of a galaxy-dominated UV background intensity $\sim 1.3\ 10^{-21}\langle f_{esc}\rangle$ cgs at $z \sim 0.5$ where $\langle f_{esc}\rangle < 20\%$ is the escape fraction of ionizing UV photons from the galaxies. Finally it is also shown that in a UV background dominated by QSOs and/or star-forming galaxies the cosmological baryon density of the Lyα clouds decreases rapidly with cosmic time possibly due to increasing bulk heating in the intergalactic medium with cosmic time.

1 Introduction

The measure of the UV background is crucial in cosmology for two main reasons: 1) it provides an estimate of the cosmological density of the photoionized gas in the intergalactic medium which is consistent with the observed Gunn-Peterson opacity; 2) it provides unique information about the nature and abundances of the sources responsible for the ionizing flux [3]. The Lya statistics near and far away from each quasar provides information about the strength of the UVB at the Lyman Limit as a function of redshift under the hypothesis that the proximity effect we see near each QSO is due to an increase of the photoionization in the nearby clouds [2]. The estimate of the UVB intensity at the Lyman edge through the analysis of the proximity effect in the Lya forest depends both on the accurate measure of the physical parameters related to the nearby QSO (e.g. the systemic redshift of the QSO and the amount of the ionizing QSO flux) and on the accurate description of the statistical distribution of the Lyα lines both in column density and redshift (see e.g. [4]). There are several results about the intensity of the UVB at $z \simeq 3$

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measured by the analysis of the proximity effect and the values range in the interval $3 < J_{-22} < 30$ in units of 10^{-22} erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}. However the results have been obtained using data of very different resolution and s/n ratio and have been analyzed using different statistical procedures.

2 The UVB and the Lyα column density distribution

There are obvious systematic effects that should be stressed in this context. It is clear that the resolution of the spectra used for the Lya statistics plays an important role. Indeed the proximity effect strongly depends on the shape (i.e. the slope for a power-law distribution) of the column density distribution. In the case of data taken at a resolution ≥ 1 Å we can only measure equivalent widths and an assumption must be made on the actual column density distribution. Nevertheless, we progressively underestimate the actual number of lines when we go away from the emission redshift since line blending becomes stronger where the number of lines increases. As a consequence, the observed decrement we see in the number of lines when we approach the emission redshift will be lower in low resolution data. For a given QSO flux, a lower decrement implies a higher UVB.

The decrement of the line number density due to the decrement of the observed column densities is a function of the shape of the column density distribution which is affected by the spectral resolution of the data and by the s/n. High resolution data ($\simeq 25000 - 35000$) with good s/n obtained at NTT by us [10] showed that the column density distribution is flatter than previously thought with a slope ~ 1.4 for log $N_{HI} < 14$ after correcting for the blanketing effects of the weak lines. At higher column densities the distribution becomes steeper with a slope ~ 1.8. At the same time the UVB value resulting from this distribution is $\sim J_{-22} = 5 \pm 1$ or $5^{+2.5}_{-1}$ if we allow for asymmetric errors. In this analysis we have adopted QSO redshift estimates derived from low ionization emission lines (OI, MgII, Hα) which are representative of the true systemic redshift of the QSO. Recent Keck data [14] confirm the flat slope ~ 1.4 at lower column densities. Analyses derived from lower resolution and/or lower s/n data assumed a single steep power-law distribution with $\beta \sim 1.7$ resulting in a value of $J_{-22} \geq 10$ [7]. In summary, taking into account the correct bending of the column density distribution and the often higher systemic QSO redshifts provided by low ionization QSO emission lines we obtain a J value definitely lower than 10^{-21} and more similar to what expected from the QSO contribution at $z \sim 2 - 3$ [13]. Moreover there is no indication of any appreciable redshift evolution of the UVB in the redshift interval $z = 1.7 - 4.1$ [10].

Of course this measure relies on the assumption that almost all of the observed proximity effect is due to the increased photoionization level near each QSO. However since high resolution spectra are taken for the brightest high z quasars, gravitational lensing can be important. Indeed gravitational lens-

ing can bias the estimate of the ionizing UVB. If lensing brightens the QSO continuum then the QSOs are intrinsically fainter than they appear, and J is overestimated [2]. The fact that the deficiency of lines in QSOs of different redshifts is correlated with luminosity but not with redshift suggests that the statistical weight of the gravitational lensing effect is small [4]. However, comparison of the proximity effect in lensed QSOs with unlensed objects would be an interesting test of the photoionization model for the proximity effect. A good example of this effect is shown by the high resolution spectrum of the QSO 1208+10 (Fontana et al., these proceedings) where the analysis of the proximity effect in its spectrum shows that the QSO is lensed and at the same time that the proximity is strongly dependent on the QSO luminosity, as expected from the photoionization model of the proximity effect.

3 The spectral shape of the UVB and the temperature of the Lyα clouds

In the previous sections we have seen that the value $J_{-22} \simeq 5$ obtained from the photoionization model of the proximity effect is not far from that predicted from the quasar contribution at $z = 3$. However, the absence of a strong redshift evolution in the UVB implies that at $z \sim 4$ this agreement is not longer valid and a discrepancy by a factor 3 does appear. For this reason we have to look for possible different ionizing sources like star forming galaxies. Further information on the nature of the ionizing sources comes in particular from the SiIV/CIV ratio which is a sensitive function of the UVB shape between the HI and HeII edge. It has been shown that a QSO dominated UVB produces a J ratio between the HI and HeII edges $S_L \sim 30$ at $z = 2 - 4$ [13] while a galaxy dominated UVB provides a value $S_L > 300$ [17]. Thus a measure of the SiIV/CIV ratio can be translated in a measure of this UVB ratio. We have obtained interesting measures from $z = 2.8$ up to $z = 3.8$ for optically thin Lya clouds obtaining SiIV/CIV values in the range 0.1-0.6. These large values imply a jump $S_L \geq 100$ specially at $z > 3$ and confirm the increasing trend with increasing z already discussed by Cowie and Savaglio in these proceedings (but see also the Boksenberg paper in these proceedings). This trend suggests an evolution of the S_L parameter that at $z \sim 2.5$ is consistent with that predicted from the quasar population while at $z = 3.5$ is more consistent with the value predicted by a star-forming population.

It is interesting to note that a possible evolution of the UVB shape can also explain the evolutionary trend observed in the minimum temperature of the Lya clouds. Indeed Kim et al. [14] found that the lower envelope of the Lya doppler parameter, which is a representative measure of the phtoionization temperature of the Lya clouds, increases for decreasing redshifts, from b=15 at $z = 3.7$ to $b = 24$ at $z = 2.3$. On the other hand, the presence of a strong HeII jump at the HeII edge reduces the He contribution to the heating rate [18, 12]. The low b values and temperatures $T \sim 20000$K observed at $z > 3$

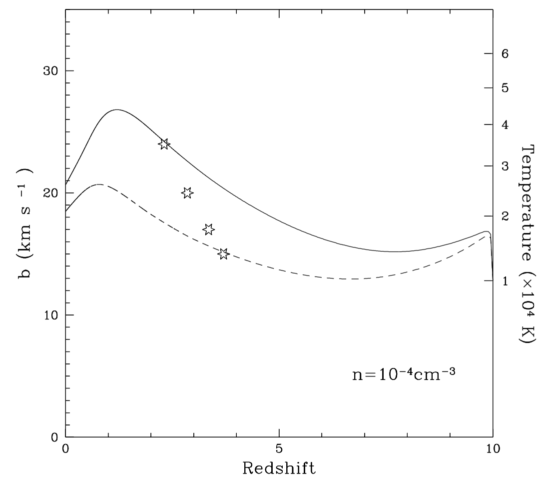

Figure 1: Evolution of the Doppler parameter b as a function of redshift for a constant cloud density $n = 10^{-4}$ cm^{-3}. Continuous curve: a power-law UVB with spectral slope -1.5 is adopted; dashed curve: the same with a further jump by a factor 100 at the HeII edge. Data points are from Kim et al. [14].

can be reproduced in large photoionized clouds.

Recently a new photoionization model has been proposed by Ferrara & Giallongo [9] where Lya clouds are photoionized by a time-dependent UVB, including non-equilibrium ionization effects. This model shows that it is possible to account for low temperatures (T=15000K or $b = 15$) at $z \geq 3$ if the reionization epoch occurred at $z \gg 5$ and the UVB has a jump by a factor 100 at the HeII edge. A trend towards smaller b with increasing redshift is present in the redshift interval $z = 1 - 5$ even for a fixed UVB shape because of the cosmological evolution of the inverse compton cooling on the CMB. However this evolution is not sufficient to explain that observed and an evolution of the jump should be invoked from a value ~ 100 to e.g. ~ 10 for a cloud with $n \sim 10^{-4}$ (Fig. 1). Thus the evolution in the UVB at the HeII edge drives both the observed SiIV/CIV evolution and the temperature evolution of the weaker Lya clouds.

4 The Galaxy UV background and the redshift evolution of the baryon density of photoionized gas

In presence of a large UVB jump at the HeII edge, hot massive stars in star forming galaxies could be considered as important contributors to the UVB. It has also been shown that the ionizing UV flux that accompanies the production

of metals at high-z can be comparable to the QSO contribution if a fraction $\sim 25\%$ of the UV radiation emitted from stars can escape into the intergalactic space [16]. On the other hand, at low and intermediate redshifts, the Canada-France redshift survey [15] has provided new information on the properties and evolution of field galaxies at $z < 1.3$. The luminosity function of blue galaxies in the Canada-France Redshift Survey shows appreciable evolution in the redshift interval $z = 0 - 1.3$, and generates a background intensity at 1 ryd of $J_L \approx 1.3 \times 10^{-21} \langle f_{\rm esc} \rangle$ ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} at $z \approx 0.5$, where $\langle f_{\rm esc} \rangle$ is the unknown fraction of stellar Lyman-continuum photons which can escape into the intergalactic space, and we have assumed that the absorption is picket fence-type. It has been argued that recent upper limits on the local UVB $\sim 8 \times 10^{-23}$ (from the Hα surface brightness of nearby intergalactic clouds) constrain this fraction to be $\leq 20\%$ [11]. If we adopt $\langle f_{\rm esc} \rangle \sim 15\%$ as a fiducial value for the escape fraction, the ensuing UVB is found to evolve little in the redshift interval between $z = 0.4$ and $z = 4$. This small evolution of J could have interesting consequences on the evolution of the baryon fraction associated with the photoionized Lyα clouds [11]. Indeed the mass density parameter depends on the volume filling factor times the average total volume density of the clouds. Assuming photoionization equilibrium this relation can be recast as a function of the typical observable quantities like J, the size l along the line-of-sight and the number density of lines as a function of (z,NHI). It is possible to notice that Ω depends only weakly on J and on the typical cloud size and geometry. The dominant factor is the number density evolution of the clouds ($\Omega_{\rm IGM} \propto (JR)^{1/2} dN/dz$).

We can compute the line contribution to Ω integrating over the known column densities and z distributions. The main parameters subjected to substancial uncertainties are the cloud sizes and geometry. From the statistical coincidence of absorption lines in closely separated quasar pairs, sizes ~ 200 kpc are derived at $z \sim 2$ [5]. Observations at lower redshifts show even larger sizes ~ 300 kpc independently of the cloud structure and geometry [8]. The mild evolution implied by these preliminary measures is consistent with the expectations of the standard CDM scenarios where the dominant effect appears to be the Hubble expansion. Thus we have assumed that the typical cloud sizes increase with cosmic time following the cosmological expansion. We can see that at $z \sim 4$, $\Omega_{\rm IGM}$ may account for all of the nucleosynthesis baryons of the universe for clouds with thickness in the range $100-300$ kpc (Fig. 2). Since J remains constant between $z = 2 - 4$, if the sizes do not evolve faster than what expected from the Hubble expansion then the significant evolution of Ω in this z interval is mainly driven by the evolution of the line number density. At lower redshift the evolution is mainly driven by the small evolution in the $(JR)^{1/2}$ factor since the observed number density is nearly constant as derived by the HST observations [1]. A plausible explanation for the high z evolution appears to be the additional heating of the absorbing gas at temperatures $T \sim 10^{5-6}$ K by the gravitational accretion into progressively more massive halos, with higher velocity dispersions, or by collisional ionization from super-

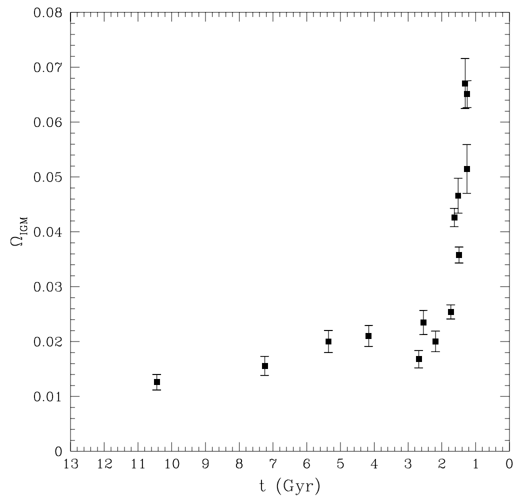

Figure 2: Mass density parameter as a function of cosmic time. High z points ($t < 3$ Gyr) are derived from our optical Lyα sample [10]. Low z points are derived from the HST Lyα sample described in [1].

novae winds. The easiest way for finding collisionally ionized, cosmologically distributed material at $T \geq 10^{5.5}$ K is to look for OVI absorption. The recent results of the first survey for OVI 1032, 1038Å absorption lines in QSO spectra [6] suggest the presence of a substantial cosmological mass density of hot, collisionally ionized gas at $\langle z \rangle = 0.9$. If the bulk heating were mainly due to supernovae explosions in spheroidal systems, the strong evolution of $\Omega_{\rm IGM}$ observed between $z = 2$ and $z = 4$ could be triggered by the star-formation activity in galaxies at high redshift.

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